

Scientific Pluralism : the battle of High Temperature Superconductivity

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Abstract

The early development of conflicting theories (i.e. one aspect of scientific pluralism) about the microscopic mechanism of High Temperature Superconductivity is described. The biographical roots of this diversity are stressed, as well as its subjective/objective roots. Scientific pluralism is discussed in relation with this study, as well as various philosophical teachings about relativism, the Duhem-Quine thesis on the underdetermination of theory by facts, and the dialectics of knowledge and nature.

1 Introduction

This paper is interested in discussing a current puzzling situation in contemporary physics: a plurality of theories have emerged very rapidly upon the discovery, in 1986, of High Temperature Superconductivity (hereafter HTS). Understanding how, why, and if HTS is a new phenomenon has led to a variety of theoretical proposals, which have not stopped since then to confront each other.

1.1 Scientific pluralism

What is at stake in a number of discussions about conflicting theories may be interpreted as the question of “scientific pluralism”: can it be that two or more conflicting theories account for the same phenomena, or account for the causal powers of the same objective real entities?

Dickson [1] defines scientific pluralism as “*...the existence or toleration of a diversity of theories, interpretations, or methodologies within science*”.

Following Hillary Putnam [2], who discusses how things (e.g. electrons) are named, and how theories evolve, all sorts of incompatible accounts of the thing

appear, all of which agree in describing various causal powers which may be employed while acting on nature.

Cartwright [3] emphasizes that in several branches of quantum mechanics, searchers may use a number of different models of the same phenomena. They can be mutually inconsistent, and none is the whole truth.

Dickson asks: "*How can one be a pluralist about science while respecting the (approximate) validity of our best scientific theories?*" In the course of his paper, he defends his own admission that as far as quantum mechanics is concerned, pluralism is justified and acknowledges the existence, and toleration of a diversity of contradictory theories. He writes: *I shall address the most obvious and serious objection to such a view...namely, that it places the scientifically minded person in the intolerable position of explicitly endorsing contradictions within science (as a matter of principle and not merely as a pragmatic matter). To do so is to reject the scientific enterprise.*

The authors in references [1, 2, 3, 4] admit that there might be pluralism in theories, in various guises. But admitting ontological contradictions within the thing seems to all authors, except perhaps Putnam, to be prohibited and intolerable.

A straightforward way out of the problem of scientific pluralism is to adopt one version or another of relativism. Following Kuhn[5] in *The Structure of Scientific Revolutions*, "scientific theories are beliefs shared by groups of persons"¹. If such is the case, if theories are merely social constructions, as other authors contend [6, 7], contradictions between theories and battles between theorists can be accounted for by social, cultural, historical differences between "groups of persons": they do not signal anything about ontological contradictions.

Dickson describes various sorts of pluralisms (it seems one may define 27 types). What I have been defending in a previous paper [8] is that contradictions in epistemics may reflect disagreements between erroneous vs correct theories, etc., but may also reflect ontological contradictions. One must free oneself from the secular aristotelian prohibition – which does not mean dismissing aristotelian logic altogether, in its own domain of validity – and face the possibility that accepting contradictions in nature is a way to save the scientific enterprise when science is pluralist.

I do not agree with most things Dickson says about quantum mechanics². I stress here that he, a philosopher convinced of the aristotelian prohibition of contradictions, is constrained to admit them as a true feature of theory.

In the above quoted paper [8], I have discussed the Quantum Hall Effects. I have stressed that Laughlin's theory of the QHE seems to have no theoretical rival, to be no example of pluralism in theory. However, a contradictory theory, the insulating Wigner Crystal proposal is in fact valid in certain magnetic field intensities or electronic density ranges, different from those where Laughlin's theory describes things with great success. This is due to a competition of two qualitatively different ground states within the free energy of the 2D electronic

¹Kuhn himself has been critical on the relativistic interpretation of his views.

²Such as stating that quantum mechanics has no dynamics. I cannot enter in details here about these disagreements.

liquid under magnetic field. The analogy with the ice-liquid transition in water helps understand that there is no complete exclusion of one dominated state from the dominant one: space and time dependent correlations reflecting the tendency to form the dominated phase generally exist in the dominant one³. Contradictions in epistemics may well reflect, at times, ontological contradictions: opposites may coexist in nature, and combine in ways which depend on the way their causal powers develop in the world. The lesson is that phenomenal manifestations of the same object of nature differ when one pole of an ontological contradiction dominates, or the reverse. Is this notion of interest in the problem of High Temperature Superconductivity? This question is central to this paper.

1.2 High Temperature Superconductivity and scientific pluralism

The history, physics and theory of Superconductivity are rich with surprises, suspense, and, in the last 29 years, with fierce scientific battles among theorists and experimental groups. Never before in the history of science have so many papers been published about a specific topic – probably more than 100 000 at the times of this writing – with no agreement in sight about the theoretical understanding of the microscopic mechanism of what appeared as a coup de théâtre in 1986: the astonishing discovery by an aging and obscure scientist – and his assistant –⁴ of superconductivity, at temperatures much higher than ever reached before for this phenomenon, in compounds where no educated theorist, except perhaps one or two⁵, would ever had bet one cent on its appearance [10].

As I had started writing this paper, I stumbled upon a review article on the same topic [11]. The author writes about superconductivity:

One cannot write the history of a war when it is still raging and this is certainly applying to the task we are facing dealing with the theory of superconductivity in the post BCS era ⁶. *The BCS theory was of course a monumental achievement that deserves to be counted among the greatest triumphs in physics of the twentieth century. With the discovery of high-Tc superconductivity in the cuprates in 1986 a consensus emerged immediately that something else was at work than the classic (i.e. phonon driven) BCS mechanism.*

As for many cases of scientific discovery, superconductivity first erupted in the world of scientific knowledge in 1911 – long before what is the topic of this paper – as a consequence of a scientific and technological advance. Kammerlingh Onnes [12], in 1908, managed to liquidify Helium at the incredibly – at

³In the case of first order transitions between different phases, this is especially manifest in the coexistence phase.

⁴Thereafter both were jointly awarded a Nobel Prize...

⁵See however reference [9]

⁶The BCS theory was the recognized theory for the vast majority of superconductors known before 1986

the time – low temperature of about 4 degrees Kelvin ⁷. This allowed to explore the properties of matter within new, extended ranges of parameters. With this achievement, Kammerlingh Onnes and his collaborators could endeavour to study the behaviour of condensed matter at hitherto unexplored low temperatures. Physics at the time was very much geared to exploring properties of metals and alloys, because of fundamental reasons, and also because of the industrial interest in such bodies, in particular because of their electrical and thermal conducting properties. It was already known that down to liquid nitrogen temperatures (around 70 degrees K) all metallic resistivities were decreasing functions of temperature. Various laws describing this decrease had been observed in various metals. When the laboratory in Leyden studied the resistive behaviour of Mercury (noted Hg), a mysterious abrupt drop in resistivity was observed at 4 degrees K, and the metal seemed to become a perfect conductor! Various metals were found then to exhibit a similar behaviour, at the so called “critical temperatures” T_c which are characteristic of each pure metal. It took twenty more years to realize that this phenomenon was not simply a perfect conductivity, but a conductivity of a special type: it expels the magnetic field [13] from the volume of the metal⁸. This is not what would happen in a normal metal if its resistivity became zero⁹.

The long and difficult quest for a theoretical understanding for this phenomenon is a fascinating story in itself, but it is not the topic of this paper. What is important as an introduction for the purpose of this paper is that a major theoretical advance (quoted above as the BCS theory) was achieved by Bardeen Cooper and Schrieffer [14] in 1958 when they published a revolutionary theory: superconductivity was due to a breakdown of the normal metal electronic structure: instead of behaving as almost independent particles governed by Fermi statistics, electrons (which have half integer spin and therefore are fermions) interact with lattice vibrations (called phonons) of the metallic crystal. The latter may be viewed as sort of glue which dominates the repulsive Coulomb interaction between electrons (incidentally, attractive vs repulsive interactions are yet another example of contradiction within the same thing). As a result they become associated in pairs, which are called singlets, have zero spin, and are bosons. Identical bosons had been shown by Bose and Einstein to condense in a superfluid state a low enough temperature. A superfluid state of charged particles is a superconducting state. Ten years of intense exploitation of the BCS theoretical advance followed, somewhat along the lines of what Kuhn called normal science [5]. New theoretical entities became familiar terms: order parameter, phase coherence, penetration depth, vortex phase, etc.. The order parameter – in the case of BCS superconductivity a complex number – characterizes the new superconducting quality: it starts from zero at the superconducting critical temperature when the temperature decreases, and its intensity grows up to a maximum at zero temperature, with thermal variation

⁷Nowadays there are ways to reach temperatures of a millionth of a degree...

⁸For sufficiently low fields; the story is more complicated where the magnetic field intensity is larger than a so-called critical field called H_{c1}

⁹for example in perfectly pure metal.

laws which were determined experimentally and explained theoretically within the BCS theory. Magnetic fields, and magnetism at large, were well identified as detrimental to (contradictory with) superconductivity and as a cause for its destruction. New devices appeared [15], based on quantum properties of the superconducting state in the presence of magnetic fields. They are now standard tools for scientific investigation, or industrial and medical applications.

Some years around 1970, it appeared to the overwhelming majority of physicists and science managers – public or private – that the (scientific) gold rush to superconductivity had exhausted its scientific novelty deposits. Science leaders who had been prominent in developing the field dropped it as a research program altogether, more or less abruptly, as miners abandon a gold mine when its yield becomes negligible. Scientific teams were disbanded¹⁰ and geared to other fields: every thing about superconductivity was known. It had become *an obsolete field* [16]. The loss of interest was also due to the quite commonly shared view among physicists that the highest possible superconductivity temperature on the planet earth would never exceed 25 K by more than a few degrees. This rule, which had been formulated empirically by a well known experimentalist meant that superconductors would remain for ever a laboratory phenomenon, with almost no industrial application.

Only a handful of searchers, mostly aging and obscure ones, kept trying to find ways of realizing higher superconductivity temperatures. A major industrial and environmental interest, to this day, is to find ways of storing electricity in a cheap way: superconducting currents, circulating in a superconducting ring, do not suffer the costly energy losses due to Ohm’s law for usual electric currents: they last –in principle – for ever. Finding ways of storing electrical energy as one stores chemical energy in coal, oil, or...dynamite, is a long lasting industrial dream. If this storage process requires prohibitive costs to cool down conductors to such temperatures as 20 K, the costs exceed the benefits.

When High Temperature Superconductivity (hereafter HTS) was discovered, this dream suddenly seemed to come true. Whole teams of physicists rushed to study, understand and improve the totally new and unexpected material – chemically doped copper oxides – which exhibits HTS.

Figure 1 shows a schematic view of the chemistry and structure of a typical HTS material. One should add to Figure 1 that by altering the stoichiometry of various chemical components, such as Oxygen, or substituting a small concentration of La atom by Sr atoms, or some other chemical manipulation, one can suppress an equivalent concentration of electrons – i.e. inject “holes”–. In fact the stoichiometric compound (no hole) is an antiferromagnetic (AF) insulator, which becomes superconducting with increasing superconducting temperature upon increasing the concentration of holes.

Very quickly the family of doped copper oxides became quite large; later on new families were discovered, such as Fe pnictides. As of today, the largest

¹⁰In Japan, a small team of scientists was instructed by the science ministry to keep watching the physics reviews in case some improbable unforeseen novelty appeared in the field of superconductivity.

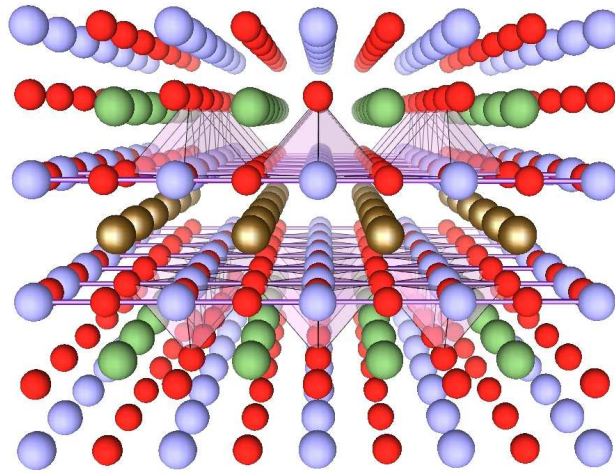


Figure 1: This figure exhibits the atomic structure of a typical HT Superconductor: contrary to the vast majority of (lower temperature) BCS superconductors, which have a much simpler chemical structure and a much simpler (usually cubic) crystallographic one (in one guise or another)), this crystal is formed by parallel sheets of Cu-O (Copper oxide) planes. The “red” atoms here are oxygen atoms, the “blue” ones are Cu (Copper)atoms; two Cu-O planes are separated by “brown” atoms (such as Yttrium or Lanthanum while “green” atoms are divalent metals such as Ca or Ba. A large family of HT Superconductors exhibits the common feature of weakly coupled Cu-O planes which have a basic square elementary cell. The occurrence of linear arrays of Oxygen chains between copper planes is specific to the particular chemical (YBaCuO) shown above. I am indebted to Julien Bobroff for providing me with the file for this figure.

known superconductivity temperature is that of a Bismuth Copper oxide compound and is around 150 K, i.e. some 80 K larger than that for liquid Nitrogen.

Thirty years after HTS was discovered, its fundamental mechanism is still the object of passionate debates among physicists.

The aim of this paper is to explore some philosophical lessons taught and questions raised by the HTS story until now. Putting aside the ontological question about the reality of HTS, which is sufficiently established by all converging tens of thousands of experiments and industrial applications, the main discussions will be about:

- scientific pluralism [1]: why are there so many theoretical views about the microscopic explanation of HTS?
- the subjective roots of this diversity;
- the objective (ontological) roots of this diversity;
- the Duhem-Quine thesis about the “underdetermination of theory by experiments”[17, 18]. Is the war mentioned above doomed to last forever?
- the lessons taught by this story from the point of view of the dialectics of knowledge and/or of nature [8, 19].

2 Historical development of different theories of HTS

2.1 Agreements and disagreements: subjective contradictions

- Agreements.

As soon as the experimental paper on the new HTS appeared, a flurry of theoretical differences among the various theories of the phenomenon appeared, on a background of universal theoretical agreement. The agreement was, with no exception known to me, that any theory had to account for the instability of the normal electronic system on the basis of formation of bosonic electron pairs. The HTS displays zero resistance and the Meissner effect, it is a “spontaneous breaking of the gauge invariance” of the normal electron system. This is the common background for the different theories concerning the microscopic mechanism of HTS.

- Disagreements.

Disagreements had their roots in the evaluation by the various schools –should I say chapels? – of the specific reason why the new material was falsifying the previous wisdom on the formerly known superconducting BCS material. Some of the disagreements are deduced by inspecting the figure 1. Depending on which structural property of the new material

is deemed to be at the basis of the new behaviour, different theoretical proposals will emerge. The specific Copper oxides structural features, as compared to “ancient” BCS metals are:

1.– contrary to most BCS metals which have cubic symmetry, HT Superconductors are organized as stacks of CuO planes –with a square array of Cu atoms separated by Oxygen – in weak electronic contact with each other, as these planes are in general separated from each other by a layer of inert atoms. In fact, differing on the specific HT Superconductor, the structure may have separated CuO planes, or sandwiches of two or more CuO planes separated from other sandwiches. HTS are anisotropic crystals with a preferred symmetry axis perpendicular to the CuO planes.

2.–In a CuO plane, since each Cu carries one outer electron available for conduction, the system of conduction electrons – if repulsive Coulomb interactions are neglected – should form a two-dimensional (2D) square Fermi surface occupying half of the available electronic states. This is in contrast with the 3-dimensional (3D) spherical Fermi Surface considered by the BCS theory.

3.– The oxide character of the HTS compounds is quite different from the simple monoatomic structure of most BCS superconductors: the chemical structure is qualitatively more complex.

4.– An astonishing feature of the CuO HTS is that the isolated CuO plane is theoretically a textbook example of an AF insulator: each Cu carries an electron bound to this atom. Two electrons on neighbouring Cu atoms are coupled ¹¹ antiferromagnetically, which means that the electronic lattice, at zero temperature should be a regular Néel array of localized spins with alternating spin direction from atom to atom, resulting in a so-called “Mott insulator”. The latter is based on the notion that Coulomb interactions are so strong between electrons that they are constrained to stay apart and stay localized each on its Cu atom. The AF order results from a small energy gain when neighbouring spins are antiparallel. This is in contrast with item 2 above, where Coulomb interactions are assumed to be negligible, so that electronic wave functions spread over the whole CuO plane, turning the crystal with one electron per atomic cell in a good metal. Furthermore, the well established experimental fact that HTS appears as emerging upon doping a magnetic material was at variance with the BCS wisdom that magnetism destroys superconductivity.

5.– In addition doping the insulating crystal to turn into a HTS inevitably introduces disorder in the lattice.

¹¹by a coupling mechanism known since the fifties called super-exchange.

2.2 The subjective/objective biographical roots of scientific pluralism in the history of HTS.

Below, I list some of the main conflicting theoretical proposals which have been formulated very early on, and how each has been rooted in the past scientific activity of its champions. They are ordered in increasing degree of novelty with respect to the BCS theory.

- F. BCS picture with singularity in the density of electronic states states.

This picture has been developed by Friedel and collaborators, based on their BCS theory in 1970 for some of the superconductors with the largest known superconductivity temperature known before 1986 (about 21 K). A basic assumption of this approach is that above the superconducting temperature the metallic state is normal and has a well defined Fermi surface. The interaction energy between electrons is supposed in this picture to be much smaller than the band width, and electron-phonon interactions play the same decisive role as in the BCS theory.

The Friedel proposal in 1970 had been based on the notion that in *A15* compounds, the quasi one dimensional structure¹² leads to a large peak in the electronic density of states at the Fermi level. Within BCS theory, such a peak produces a larger superconducting temperature than a lower regular flat density of states.

Friedel and collaborators argued that in CuO planes, such a singularity arises in the density of states precisely for one electron per lattice cell in the CuO lattice. Neglecting Coulomb interactions, they adapted their previous theory to the new material and attributed to phonons, as in the BCS theory, the role of glue between pairs of electrons. The only new experimental feature which this proposal takes into account is the crystal anisotropy, as shown in fig 1

- S1 The Spin Bag picture.

Schrieffer [21] developed a theory based on repulsive electron-electron interaction in a large energy band. The starting point is similar to Friedel's, namely the existence of a well defined Fermi Surface at temperatures larger than the superconducting temperature. In certain cases, a geometry of the Fermi surface (a so-called "nesting property") each electron spin will surround itself with a cloud of spin polarization. Schrieffer argued that under certain conditions, two such clouds could favour the formation of spin singlets. In other words, he suggested an alternative route to the superconducting phase: instead of an attraction between electrons mediated by phonons, as in the standard BCS phenomenon, the attractive electron-electron interaction is a result of spin fluctuations, which are themselves the result of repulsive electron-electron interactions.

¹²A generic property of so called *A* – 15 crystals such as *Nb₃Sn* or *V₃Si* .

Some twenty years before, Schrieffer and col. had worked out a spin fluctuation theory to account for the transport and thermal properties of almost magnetic metals such as *Pd* and *Pd – Ni* alloys [22, 23]. This theory argued that spin fluctuations destroy superconductivity. On the face of the HTS discovery, a contradictory result was found to be possible, under conditions not explored previously!

- S2 The Renormalization Group with Van Hove singularity.

An original picture was proposed by Schulz [24]. He devised a brilliant Renormalization Group approach to electron-electron interactions in a half filled square lattice. A Van Hove singularity is a singular property of the density of electronic states when the Fermi Surface and the boundaries of the Brillouin zone come in contact. This feature has important consequences. Schulz explored (before Schrieffer) the new scenario based on repulsive electron-electron interactions. Even though the starting point of his study is, as in item F and S1 above, that of weak (compared to the band width energy K) electronic repulsive interactions U , the Renormalisation Group (RG) treatment of the many electron-electron interaction processes is based on the recognition that various different symmetry breaking phases, associated to different electronic processes, are competing, in the case of a square Fermi surface and Van Hove singularities¹³, with one another. Among them a superconducting phase with a novel order parameter dubbed d-wave is competing with an antiferromagnetic insulating one. Taking into account a slightly more realistic Fermi surface (not exactly a square) it was easy to show, using Schulz' approach, that the most stable phase could indeed be a d-wave superconducting one [25]. Prior to the discovery of HTS, Schulz had been working on one dimensional electron systems, where the RG allows to sort out the various symmetry breaking ground states. A surprising result of his RG approach, along the work in ref. [25], is that repulsive electron-electron interactions may lead to a stable superconducting phase. As for the authors of ref.[25], they had been working, before the discovery of HTS in 1986 on realistic Fermi Surfaces in quasi 1-D conductors¹⁴.

- M. The bipolaron picture.

Mott [26] also attributed HTS to electron-ionic lattice interactions. Famous for his numerous contributions to physics, he had – among others – published pioneering studies of transition metal oxides, and of their electronic states. In particular he had pointed out, many years earlier, that due to strong electron lattice interactions in insulating oxides, isolated electron would deform the lattice by Coulomb attraction between electrons and the ionic lattice, forming so-called polarons [27]. He then argued that in HTS such polarons could form pairs (due to a lowering

¹³Which is the case in a half filled square lattice.

¹⁴Schulz' pioneering work is not always recognized. Due to his untimely death, Schulz was not able to disseminate his results in conferences, meetings, etc..

of elastic energy) dubbed bi-polarons, which are bosons. Bosons then condense to form a superconducting state.

- A. The Resonating Valence Bond picture. The Mott insulator parent of HTS.

P. W. Anderson (PWA) [28] proposed a revolutionary “Resonating Valence Bond” (RVB) theory. His approach took the view, contrary to Friedel, Schrieffer and Schulz, that Coulomb interactions (of the order of $U = 100000K$), far exceed, in the CuO plane, the band width energy (of the order of $K = 10000K$). His starting point was that the undoped cuprate was a Mott insulator. He first suggested that in the case of the square lattice with one electron per site, the ground state could be different from the expected Néel AF state. PWA instead proposed that neighbouring spins form singlets, and described a massive entanglement of products of singlet states “resonating” with each other. At half filling, the ground state would be a new insulating quantum spin liquid. But if a sufficient concentration of “holes” (empty states) are injected in the lattice, the doped system of entangled singlet states becomes superconducting with a temperature of order of the kinetic energy¹⁵. His initial formulation predicted a superconducting order parameter of symmetry s, as in the BCS theory; this was quickly revised in favour of d-wave, for experimental and theoretical reasons. The d-wave singlet is favoured by strong repulsive Coulomb interactions, because it has zero amplitude for the two electrons of the singlet to be simultaneously present on the same site.

The RVB proposal had been first developed by PWA, in 1973¹⁶, years before the advent of HTS, as an alternative ground state to the Néel insulating (AF) ground state for certain Mott insulators[29]. PWA gave an example of a “railroad trestle” (a model with two coupled infinite straight lines with a regular array of spin 1/2 electron and exchange coupling in-chain and inter-chain). His novel intuition in 1986 about the CuO square with doped holes was that the system of holes embedded in the RVB spin liquid would be superconducting. His original prediction of the magnitude of the superconducting temperature nurtured wild hopes for extremely high ones (about 10 000 K!). Another novel feature of this proposal was the separation of spin and charge degrees of freedom into “spinons” and “holons”, in the RVB state: a spectacular breakdown of the independent electron picture.

Anderson’s proposal received enthusiastic support by a large fraction of theorists, because of its novelty and its audacity which seemed to correspond to the novelty of the HTS material, and to that of spectacularly high superconducting temperatures. Another sizable part of the theorists’ population, rejected it, precisely because of its novelty and audacity: basing the new phenomenon on repulsive interactions, while from 1958 to

¹⁵This point was quickly corrected[30] to an estimate of the order of $K^2/4U \approx 250K$.

¹⁶In the Materials Research Bulletin.

1986 all superconducting material had been understood on the basis of attractive (el-phonons) seemed hard to swallow...

- L. The anyon superconductivity picture.

Within the new paradigm of a superconductivity scenario based on strong electron-electron repulsions, Laughlin [31] developed the so called “anyon model of HTS”. He focused also on the behaviour of electrons confined to a plane. His main new idea was that a uniform magnetic field would spontaneously arise and organize electrons in a superfluid liquid similar to the Fractional Quantum Hall liquid which he had so brilliantly studied in the early eighties and for which he was to be awarded the Nobel prize. In terms of audacity and novelty, his work passed that of Anderson. He used the wisdom acquired in the study of the Quantum Hall Effects (QHE). He showed that a (2D) gas of anyonic particles had to be superconducting. Anyonic particles can only exist in 2D and have statistics governed by any phase angle upon interchange of two particles, contrary to bosons or fermions, the statistical angle of which is, respectively 2π , or π . Anyons are believed to exist –on very firm theoretical grounds – in the QHE. A simple theoretical picture of the spontaneous emergence of a uniform magnetic field in a 2D lattice of strongly interacting electrons doped with holes was given in [32] under the name “flux phase”. A major novelty in Laughlin’s scheme is that HTS might be the simultaneous occurrence of both gauge invariance and time reversal spontaneously broken symmetries.

The list of theoretical proposals given above is by no means complete, and is limited to the very early days of the scientific battles that are still developing today [11]. Qualitatively new viewpoints have emerged later on, which are not discussed in this paper. The aim of this paper is to reflect on what we can learn about the science process from those few examples. There is no attempt here at historical rigor, although I have tried to be as truthful as I could.

3 Underdetermination of theory by facts?

At first sight, what I have sketched above seems to come in support of the Duhem/Quine thesis on the underdetermination of theory by facts. All schemes listed above claim more or less to account for the same phenomena of HTS, on the basis of different hypothesis.

As pointed out above, the differences between the theories of the microscopic mechanisms of HTS have developed on the basis of universally accepted views, together with different views on the relevant parameters for the cuprates. Within the various items I have listed above, there are classes with basic differences, along with some overlap between those.

- The band picture scheme.

One class of proposals (items F, S1, and S2 for example) are based on the idea of the domination of kinetic energy K over electronic interactions U .

This is noted $K \gg U$ and is the so called band model, which assumes the band theory of metals to be the correct starting point.

- The electron-phonon scheme.

A sub class of the previous one (item F) is based on the BCS model of electron-phonon interactions, and neglects electron-electron interactions; i.e. $U_{el-ph} > U_{el-el}$. Although I have only quoted Friedel in this context, a large body of theoretical work continues along that line.

- The doped Mott insulator scheme.

Items S1 and S2 represent another sub-class, which takes the view that $K \gg U_{el-el} \gg U_{el-ph}$. S1 and S2 differ in that S2 focuses on the Van Hove singularity. The latter is unavoidable for a half filled square lattice; S2 seems to be the rigorous way to treat the S1 “spin bag” idea, in the case of a square Fermi Surface touching the Brillouin zone.

- The Mott insulator scheme.

Another large class of theories is based on the notion that the undoped ground state of the CuO planes is a “Mott insulator”, i.e. one where $U_{el-el} \gg K \gg U_{el-ph}$. This is represented by items A,M,L above.

- Class M is simultaneous one that admits $U_{el-el} > K$ and that U_{el-ph} plays a decisive role in the formation of singlets (bi-polarons).
- Items F,S1, S2 contain the notion of a Fermi Surface in the normal (i.e. metallic) doped phase. Item M does not, since it relies on bosons which have no Fermi Surface¹⁷. The existence of a Fermi surface is now an established experimental fact.

In agreement with experimental data, all theories share the view that HTS arises when the CuO planes are doped with holes¹⁸.

An obvious lesson is that the development of theory is based on a choice of the relevant energy which dominates the HTS instability. This is, in my view, deeply rooted in the physicists’ culture which teaches to analyse nature in most cases, in terms of competing energies, (i.e. ontological contradictions in the dialectical materialist sense) as discussed in [8]. This is what Althusser called the Spontaneous Ideology of Scientists (SIS) [33].

Another lesson is that the subjective choice of leading energy parameter is deeply influenced, quite obviously, by each theorist’s scientific biography. Each leader drags along with him groups of scientists which share similar scientific biographies. This feature is probably a strongly enhanced one¹⁹ of post world

¹⁷An interesting document which describes a partial state of affairs in the HTS battles in 1998 is listed in ref. [34].

¹⁸Inter CuO layer coupling was considered later by PWA, then abandoned, due to a crucial experiment.

¹⁹Similar to-, but strongly enhanced compared with- past controversies such as the Newton-Fresnel one about the nature of light.

war science in physics: the number of topics, new phenomena, experimental techniques, theories, published papers, etc., which have appeared is such that no single scientist can grasp all the significant results which should be taken into account in the face of a new phenomenon. One looks for the lost wallet under the lamp post because this is where there is some light. But there are different lamp posts. The scientific press, the conferences allow to confront different views with one another, and with phenomena. In the case of HTS, the explosion of the number of papers has created an information bottleneck. The leading scientific review of, say, Condensed Matter physics, contains around 2000 pages per fortnight. Private publishing companies which have gained a reputation for excellence tend to favour, for financial profit, spectacular papers, with an increasing number of scientific frauds²⁰. An increasing tendency is to form groups of searchers convinced of the validity of a specific scheme, and to ignore contributions – both theoretical and experimental ones – which do not explicitly support it. International meetings are sometimes organized by groups who do not invite contradictors...

3.1 Relativism?

Should this lead to a relativistic attitude? Are theories, after all, as Kuhn wrote, beliefs shared by groups of persons? Obviously, if we consider the development of HTS theory from the start, this state of affairs reflects at least an appearance of truth. However, such a view is corrected by the fact that some of the initial theories have been discarded quickly, because some of their crucial predictions have been falsified by experiments. Laughlin's theory on HTS ref.[31, 32] has failed in its initial form because of a crucial experiment: the predicted magnitudes of magnetic fields inside the material have not been observed. Similarly, the bi-polaron theory has been discarded by most, if not all, theorists. The initial prediction, both by F and A initial proposals, that the order parameter in HTS would have spherical “s” symmetry, has been quickly corrected : the evidence that the order parameter in CuO HTS has “d” symmetry is overwhelming. The latter is unavoidable in case of a mechanism driven by el-el interactions. Those corrections, at first sight, seem to support Popper's views [36] on the progress of science. I have listed criticisms to Popper's falsification theory in ref.[8].

3.2 Crucial experiment?

Bacon [35] has introduced the notion of crucial experiment, which allows to discriminate between a truthful theory and an erroneous one. Duhem [17] has argued that there is no such thing. I have argued elsewhere [37] that Duhem's stand is destroyed by Duhem's own admittance that “ the theory of vibrating

²⁰The pressure for faking experimental results is due in a large part to the funding system of research, increasingly based on short term contracts. The latter are awarded on criteria where social features (number of citations, review impact factors, etc., play an increasing roles in most scientific institutions.

strings is certain". The notion of crucial experiment is vindicated by scientific practice and is intimately connected with the notion of truth, as I discussed in a previous paper [8].

However, it is striking that, somewhat along some of Cartwright's ideas [3], in the case of HTS, various different theories claim they account equally well – sometimes equally badly – for the same phenomena. The search for the “smoking gun”, in the HTS literature, synonymous with “crucial experiment”, is still going on.

Some experiments have been crucial to discard some theories. None, so far, has been able to pin point one and only one microscopic mechanism as the single correct one for HTS.

On the other hand, all theories discussed above have taken into account experimental features which are experimentally undisputable. What differs from author to author is the choice of the main objective feature on which theory is constructed.

3.3 Dialectics of knowledge?

It follows from this discussion that a first conclusion confirms, contrary to Kuhn, Cartwright, Rorty, Latour and others, that the process of knowledge is simultaneously subjective and objective. Sève [19] writes: *...the two poles of the cognitive process, the subjective and the objective must be recognized not only as opposite ones, but as identical: the objective part is subjective – and here the very meaning of the scientific endeavour seems to be lost – but simultaneously the conditions and limits under which the subjective part is objective become determinable.*

A great deal of activity has been centered, more recently than the history I deal with in this paper, around a specific feature of HTS at small hole doping, the so-called “Pseudo-gap phase”, which exhibits experimentally a suppression of spin excitations as the temperature is lowered, but still above the superconducting temperature. This feature is absent from the pre HTS BCS physics, so it has become central to many investigations. Again, various conflicting schemes confront each other, some with a background rooted in the items listed above, some with newer ones (stripe phases, quantum critical point, for example [11]). On top of hosts of experimental techniques known before 1986, many of which have improved their accuracy, new ones have been developed and launched against the HTS mystery. But to no avail, as of the day of this writing, as far as a consensus about the microscopic mechanism of HTS is concerned.

Drawing definite philosophical conclusions about the HTS battles seem at this time risky. Science has known century long controversies, which have generally ended up in a qualitatively new theoretical scheme which supersedes previous disagreements, such as for example the debate about discreteness vs continuity for light. The historical process of research about HTS is by no means ended. Some now believe that, behind the present state of confusion, astonishing theoretical progress on HTS may be lurking around some laboratory

corners. Far reaching consequences on our understanding of nature, far beyond the specifics of HTS itself are hoped for [11].

3.4 Dialectics of nature?

I have mentioned above the spontaneous tendency of physicists to think about natural processes in terms of conflicting scales of parameters. As mentioned in ref.[8] this has generally its origin in the dialectics of matter itself. Under conditions such that one type of energy (or free energy, or thermodynamic potential) parameter dominates, matter will express its essence through different phenomenal manifestations: order or disorder, insulator or conductor, ferromagnetism or paramagnetism, liquid or solid, symmetry or broken symmetry, etc... Understanding the different relevant scales of lengths, temperatures, magnetic fields, interactions, at work in the thing etc., is a basic skill of physicists to analyze nature. In the HTS problem, could it be that one specific aspect of the physics at hand is that various parameters are simultaneously relevant, while leading to conflicting types of order? It has been understood after a while that the primitive dichotomy between the various schools, based on whether U_{el-el} is much larger, or much smaller than the band width K is in fact not justified by quantum chemical calculations. In fact, in the HTS cuprates, $U_{el-el} \approx K$. Under such conditions the role of U_{el-ph} , and its association/opposition to U_{el-el} may be sometimes decisive for certain HTS phenomena. Other phenomena, not discussed in this paper, such as disorder, or the tendency of electrons to organize in stripes [11], are believed to be of great importance. The spontaneous breaking of time inversion symmetry à la Laughlin has not been supported by experiment in its original version, but may be revived when looking at finer details of electronic structure. What is at stake here is perhaps the relevance or irrelevance of a theoretical approach based on a binary contradiction of opposites.

The “pseudo gap” phase seems to be an example where various order parameters compete with one another [11, 38]. Sève [19] has discussed the extension of binary dialectics of nature to richer dialectics based on a multiplicity of poles. In technical words, the suggestion is that a number of free energy minima corresponding to different parameters, broken symmetries, etc., have similar magnitudes in the relevant temperature ranges, so that correlations within the material suffer multiple competing influences. This complexity seems also to be deeply connected with the structural and chemical complexity of doped HTS cuprates, in contrast with the simple structure of metals of the BCS times. It may be that exploring this path, in the theoretical physics research, as in the philosophical one, is a way to a theory and to concepts which might supersede the present conflicts between the various chapels.

In ref.[8], in the discussion of Quantum Hall Effects (QHE), I have stressed that the physics of QHE is one where the energy scale U_{el-el} is much larger than any kinetic energy scale. In that sense, the QHE physics is the opposite of simple metal physics, where the kinetic energy scale dominates. The reason for the lack of a present consensus about the HTS physics seems to be connected to the intermediate situation, with a complexity calling for qualitatively new the-

oretical concepts, as well as new philosophical developments about the dialectics of nature.

4 Conclusion

The initial development of the theoretical activity of physicists on the microscopic mechanism of HTS is a rich story involving many aspects of the practice and theory of knowledge. I have briefly pointed out some biographical and sociological features, but the main focus in this paper has been on the origins and persistence of scientific pluralism. The story of HTS seems a specially well suited (experimental) ground for philosophical inferences about both the process of knowledge and those of matter. Universal lessons have been proposed which are suggested, or confirmed, by this particular example.

I apologize to the many physicists who have contributed significant results in the field of HTS, whom I have not cited, because of the focus of this paper, because of my subjective choices in describing the HTS early history, or simply because of ignorance.

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